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ORIGINAL RESEARCH

Mortality differences among patients with trauma based on systolic blood pressure and pulse pressure: insights from a generalized additive model diagram

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Abstract

Background: Rapid recognition of shock in trauma patients is imperative for timely intervention and optimal outcomes. Conventional hemodynamic indices, such as systolic blood pressure (SBP), pulse pressure (PP) and shock index (SI), are commonly used to predict mortality but often fall short in predictive performance when assessed individually. To overcome these limitations, we applied a generalized additive model (GAM) to examine the nonlinear interaction between SBP and PP in relation to mortality risk. **Methods**: We conducted a retrospective cohort study using data from the Seoul Golden Time Registry (2019–2022) of trauma patients transported to 10 hospitals in Seoul. Receiver operating characteristic (ROC) analysis was employed to assess the mortality prediction by SBP, PP and SI; while no significant differences in survival prediction were observed among these indices, a notable correlation was found between SBP and SI. Consequently, a generalized additive model (GAM) was applied to evaluate the interaction between SBP and PP, with adjustment for confounding variables including age, sex and pre-hospital transport time. **Results**: A total of 62,680 out of 82,623 trauma patients were analyzed. ROC curve analysis revealed no significant difference in mortality prediction among SBP, PP and SI (SBP *vs.* PP, $p = 0.8347$; SBP *vs.* SI, $p = 0.3077$; PP *vs.* SI, $p = 0.4433$). GAM analysis identified a significant interaction between SBP and PP with adjusted confounding factors ($p < 0.001$). The interaction plot showed a bimodal relationship between SBP and mortality, with increased mortality risk associated with lower PP. **Conclusions**: The study confirms that the interaction between SBP and PP significantly affects mortality in trauma patients. These findings suggest that an integrated assessment of these hemodynamic indices may improve the early identification of high-risk trauma patients and optimize management decisions during pre-hospital and emergency care.

Keywords

Blood pressure; Pulse pressure; Trauma; Mortality

1. Introduction

Trauma is a leading cause of morbidity and mortality worldwide, demanding rapid and accurate clinical assessment for effective intervention. In the pre-hospital and early hospital phases, clinicians rely heavily on vital signs, with blood pressure as a key indicator of circulatory status and tissue perfusion. However, reliance on a single parameter, such as systolic blood pressure (SBP), is limited in its ability to reflect the complexities of hemodynamic changes, particularly when vascular resistance is altered.

To overcome these limitations, additional indices—such as diastolic blood pressure, mean arterial pressure, pulse pressure (PP) and shock index (SI)—have been explored to enhance risk stratification. Typically, SBP below 90 mmHg is indicative of hypotension, and a PP constituting less than 25% of SBP is considered abnormal [1]. Despite these established thresholds, the isolated use of these variables has not consistently provided optimal predictive accuracy for mortality, thereby contributing to variability in clinical decision-making.

Recognizing that the interplay between these hemodynamic parameters may offer superior prognostic insight, our study employs a generalized additive model (GAM). GAM provides a significant advantage over traditional linear models by capturing complex, nonlinear relationships and interactions between variables. This approach facilitates a more nuanced understanding of how SBP and PP jointly influence mortality risk, which may enhance early risk stratification and support tailored clinical interventions during the critical initial phase of trauma care.

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The primary objective of this study is to compare the predictive performance of SBP, PP and SI for mortality in trauma patients. Additionally, we seek to elucidate the interaction between SBP and PP using a GAM, aiming to refine early risk assessment and guide management decisions in emergency settings.

2. Methods

2.1 Study design and data collection

We conducted a retrospective cohort study based on a multicenter metropolitan registry known as the "Seoul Golden Time Registry". This registry is aimed at ensuring the quality control of the emergency medicine system (EMS) in Seoul, S. Korea. Since 2015, Seoul Metropolitan City has implemented the "Seoul Golden-Time Emergency Medicine System Project" to ensure that critically ill patients, such as those experiencing myocardial infarction, stroke, cardiac arrest and major trauma, receive appropriate management within the golden hour. Since 2019, this registry has been operating across 10 hospitals that provide definitive round-the-clock management.

Data were extracted from the Seoul Golden Time Registry, which encompasses patients transported to 10 designated hospitals in Seoul via the Emergency Medical Service System under the Seoul Metropolitan Fire and Disaster Headquarters, between 2020 and 2022. All identifiable individual information was removed. After anonymization, relevant variables, including patient demographics, hospital categories, Korean Triage and Acuity Scale levels (KTAS), trauma details, transfer interval from scene to hospital, Glasgow Coma Scale (GCS) scores, Injury Severity Scores (ISS), vital signs and clinical outcomes, were extracted.

2.2 Study population

Trauma patients who visited the emergency department (ED) through EMS from October 2020 to September 2022 were enrolled. The inclusion criterion for this study was major trauma cases who arrived alive at emergency rooms, excluding those resulting from intoxication, asphyxia, burns or drowning.

2.3 Variables

The variable of interest is whether there was survival among trauma patients at ED. Other explanatory variables included patient characteristics, pre-hospital information, and hospital information. Patient characteristics, such as age and sex (female, male), were examined. For pre-hospital information, transport interval time, receiving hospital level (regional, tertiary), and trauma details such as emergency (yes, no), intention (nonintentional, self-harm/suicide, assault, others), and mechanism were investigated. KTAS level (Level 1~Level 5), vital signs (blood pressure, pulse rate, respiratory rate, body temperature, saturation), GCS and ISS were examined for hospital information.

2.4 Statistical analysis

Continuous variables are reported as means and standard deviations (SDs), while categorical variables are presented as frequencies and percentages. To compare groups, Student's *t*-test was used for continuous variables, and the chi-square test was applied for categorical variables.

Receiver operating characteristic (ROC) analysis was conducted to assess the overall performance of SBP, PP and SI in predicting mortality based on the binary outcomes of death in the emergency department. DeLong's test was used to evaluate significant differences between the ROC curves.

A generalized additive model (GAM) was employed to identify the interaction between two variables with a nonlinear relationship with mortality outcomes in the emergency department. A GAM is a generalized linear model in which the linear response variable depends linearly on the unknown smooth functions of some predictor variables. This allows for visually interpretable outcomes, which can be presented using the "vis.gam" package in R.

All probability values were two-sided, and values of <0.05 were considered statistically significant with a 95% confidence interval (CI). All statistical analyses were conducted using R software (http://www.R-project.org).

3. Results

3.1 Baseline characteristics by survival

The study enrolled 62,680 patients with traumatic injuries during the study period (Fig. 1).

Table 1 presents the general characteristics and categorical variables according to survival status. The study cohort included 62,620 survivors and 60 deceased individuals. The median ages of the two groups were relatively similar, with no significant differences. This cohort had a notable male predominance, particularly among those who died. A significant portion of the cohort was transported to tertiary emergency medical centers (EMCs). Mortality rates were significantly associated with the Korean Triage and Acuity Scale (KTAS). Most deaths were due to non-intentional injuries, and there was no significant variation in mortality rates based on the specific mechanism of injury.

In the deceased group, GCS, SBP, DBP (Diastolic blood pressure), MAP (Mean arterial pressure), PP, body temperature (BT) and oxygen saturation (SpO_2) values were lower, while the transport interval from the scene to the emergency room (aggregated as Transport Interval), the Injury Severity Score (ISS), PR (Pulse rate), and respiratory rate (RR) were higher.

3.2 Baseline characteristics by SBP

Table 2 presents the demographic and general characteristics of patients with an SBP of <90 mmHg (the "SBP <90" group) compared to those with an SBP of ≥ 90 mmHg (the "SBP ≥ 90" group). A total of 62,680 patients were analyzed, with 606 exhibiting SBP <90 mmHg. The mean age was lower in the SBP <90 group. In terms of sex, the SBP <90 group had a higher probability of male predominance. A lower proportion of patients in the SBP <90 group were transported to a tertiary EMC compared with that of the SBP ≥ 90 group. Regarding KTAS levels, the majority of the SBP <90 group was classified as Level 3, while the majority of the SBP ≥ 90

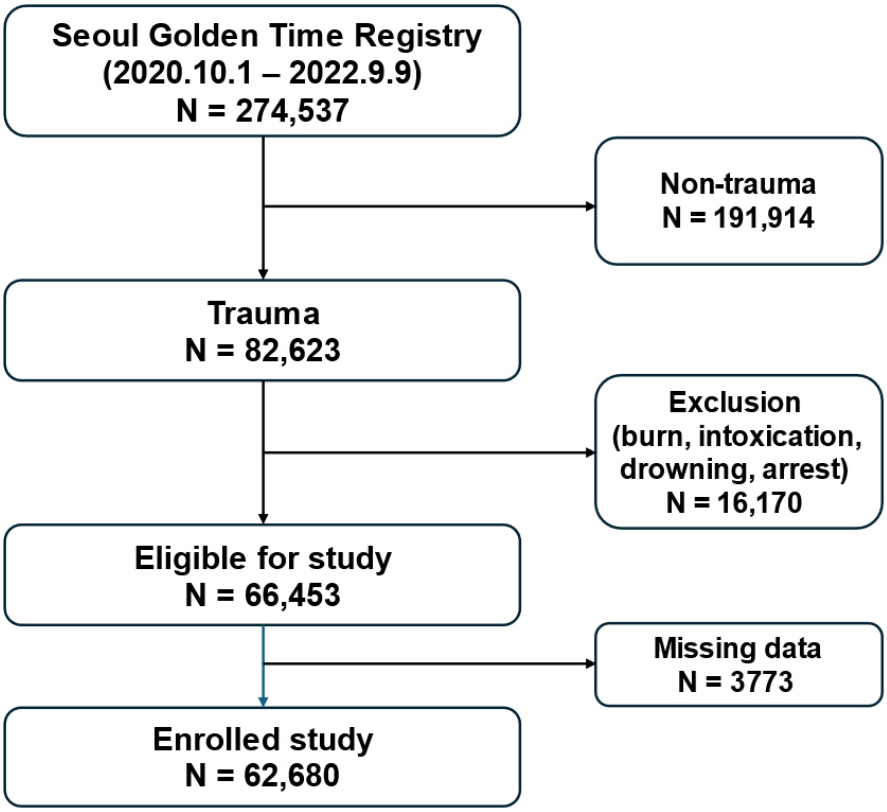

FIGURE 1. Flowchart diagram of the study population. Final enrollment is assigned except for missing or incomplete data.

group was classified as Level 4. A higher proportion of patients in the SBP <90 group were classified as having emergencies. Regarding the intent of injury, nonintentional injuries were predominant in both groups but were less prevalent in the SBP <90 group. Additionally, a notable proportion of self-harm/suicide cases were observed in the SBP <90 group.

In the SBP <90 group, GCS, SBP, DBP, MAP, PP, BT and SpO_2 were lower, while the Transport Interval, ISS, PR and RR values were greater. The visit route did not differ significantly between the groups. The mortality rate was higher in the SBP <90 group.

3.3 Baseline characteristics by PP

Table 3 presents demographic and general characteristics of patients with a PP of <30 mmHg (the "PP <30" group) compared to those with a PP of ≥30 mmHg (the "PP ≥30" group). A total of 62,680 patients were analyzed, with 2107 in the PP <30 group. The mean age was lower in the PP <30 group. In terms of sex, the differences in PP were not significant. A lower proportion of patients in the PP <30 group were transported to a tertiary EMC compared with the PP ≥30 group. Regarding KTAS levels, the majority of the PP <30 group were classified as Level 4, with the majority of the PP ≥30 group also being classified as Level 4. A higher proportion of patients in the PP <30 group were classified as having emergencies. Regarding the intent of injury, nonintentional injuries were predominant in both groups but were less prevalent in the PP <30 group. Additionally, a notable proportion of self-harm/suicide cases were observed in the PP <30 group.

In the PP <30 group, GCS, SBP, MAP, PP, BT and SpO_2 were lower, whereas Transport Interval, ISS, DBP, PR and RR values were higher. There were no significant differences in the routes of visits between the groups. The mortality rate was significantly higher in the PP <30 group.

3.4 Interaction analysis of SBP and PP

ROC analysis (Fig. 2) demonstrated that SI, PP, and SBP each exhibited moderate and comparable discriminative ability for mortality prediction, with area under the curve (AUC) values of 0.724 (95% CI, 0.653–0.796), 0.688 (95% CI, 0.630–0.746), and 0.691 (95% CI, 0.614–0.768), respectively (all $p < 0.001$). The optimal cutoff values for SI, PP, and SBP were 0.86, 34 mmHg, and 112 mmHg, respectively.

No significant differences were observed in DeLong's test for SBP *vs.* PP ($p = 0.8347$), SBP *vs.* SI ($p = 0.3077$) or PP *vs.* SI ($p = 0.4433$).

Although SBP, PP and SI each showed statistical significance, no significant differences were observed between these variables. Because of the correlation between SBP and SI, a GAM analysis was performed with SBP and PP. GAM revealed a significant interaction between SBP and PP with adjusted confounding factors ($p < 0.001$, deviance explained = 21%).

An interaction diagram was constructed to identify the relationship between SBP and PP; the interaction diagram between SBP and PP demonstrated a bimodal association between SBP and mortality, and a concurrent increase in mortality risk with low PP (Fig. 3).

TABLE 1. Demographic and general characteristics of mortality among patients with trauma.

Name	Description	Alive (N = 62,620)	Death (N = 60)	Total (N = 62,680)	*p*
Age (yr)	Mean ± SD	53.5 ± 22.9	68.7 ± 17.7	53.5 ± 22.9	<0.001
Sex					
	Female	26,989 (43.1%)	14 (23.7%)		0.004
	Male	35,631 (56.9%)	45 (76.3%)		
Hospital level					
	Regional EMC	19,287 (30.8%)	26 (43.3%)		0.049
	Tertiary EMC	43,333 (69.2%)	34 (56.7%)		
KTAS					
	Level 1	125 (0.2%)	10 (16.7%)		
	Level 2	3006 (4.8%)	39 (65.0%)		
	Level 3	20,602 (32.9%)	10 (16.7%)		NA*
	Level 4	37,008 (59.1%)	1 (1.7%)		
	Level 5	1879 (3.0%)	0 (0.0%)		
Emergency					
	Yes	58,237 (93.0%)	60 (100.0%)		0.021
	No	4383 (7.0%)	0 (0.0%)		
Intention					
	Nonintentional	57,548 (91.9%)	57 (94.8%)		
	Self-harm/Suicide	1753 (2.8%)	3 (5.2%)		0.144
	Assault	3256 (5.2%)	0 (0.0%)		
	Others	63 (0.1%)	0 (0.0%)		
Injury mechanism					
	Traffic accident	17,659 (28.2%)	27 (45.0%)		
	Falling	7327 (11.7%)	23 (38.3%)		
	Slip down	22,292 (35.6%)	7 (11.7%)		NA*
	Collision	10,019 (16.0%)	2 (3.3%)		
	Cut/Stab	4947 (7.9%)	1 (1.7%)		
	Machine	376 (0.6%)	0 (0.0%)		
Transport Interval	Mean ± SD	33.4 ± 17.0	39.6 ± 22.2	33.4 ± 17.0	0.047
Total GCS	Mean ± SD	14.6 ± 1.7	9.8 ± 5.0	14.5 ± 1.8	<0.001
ISS	Mean ± SD	9.4 ± 8.1	19.4 ± 22.2	9.4 ± 8.3	<0.001
SBP	Mean ± SD	139.4 ± 26.2	113.8 ± 40.3	139.4 ± 26.2	<0.001
DBP	Mean ± SD	80.8 ± 15.0	71.9 ± 24.2	80.8 ± 15.0	0.006
MAP	Mean ± SD	100.4 ± 16.7	85.9 ± 28.5	100.4 ± 16.8	<0.001
PP	Mean ± SD	58.7 ± 20.3	41.9 ± 23.2	58.7 ± 20.3	<0.001
PR	Mean ± SD	85.2 ± 16.0	101.9 ± 29.9	85.2 ± 16.1	<0.001
RR	Mean ± SD	18.9 ± 2.1	21.0 ± 4.8	18.9 ± 2.1	0.002
BT	Mean ± SD	36.7 ± 0.5	36.1 ± 1.0	36.7 ± 0.5	<0.001
SpO_2	Mean ± SD	97.7 ± 2.2	94.2 ± 5.9	97.7 ± 2.2	<0.001
ROUTE					
	Direct	62,019 (99.0%)	60 (100.0%)		
	Transfer	573 (0.9%)	0 (0.0%)		1.000
	Outpatient referral	22 (0.0%)	0 (0.0%)		
	Others	6 (0.0%)	0 (0.0%)		

*Transport interval, time interval from scene to emergency department (ED); GCS: Glasgow Coma Scale; ISS: Injury Severity Score; SBP: systolic blood pressure; DBP: Diastolic blood pressure; MAP: Mean arterial pressure; PP: Pulse pressure; PR: Pulse rate; RR: Respiratory rate; BT: Body temperature; SpO_2: oxygen saturation; ROUTE: Visit route; SD: Standard deviation; EMC: Emergency medical center; KTAS: Korean Triage and Acuity Scale. *p-value could not be calculated using chi-square approximation due to small expected counts; exact test was applied.*

TABLE 2. Demographic and general characteristics associated with systolic blood pressure.

Name	Description	SBP ≥90 mmHg (N = 62,074)	SBP <90 mmHg (N = 606)	Total (N = 62,680)	*p*
Age (yr)	Mean ± SD	53.5 ± 22.9	50.1 ± 23.4	53.5 ± 22.9	<0.001
Sex					
	Female	26,754 (43.1%)	235 (38.7%)		0.033
	Male	35,320 (56.9%)	371 (61.3%)		
Hospital Level					
	Regional EMC	19,011 (30.6%)	273 (45.0%)		<0.001
	Tertiary EMC	43,063 (69.4%)	333 (55.0%)		
KTAS					
	Level 1	107 (0.2%)	26 (4.3%)		NA*
	Level 2	2854 (4.6%)	211 (34.8%)		
	Level 3	20,391 (32.8%)	226 (37.3%)		
	Level 4	36,891 (59.4%)	135 (22.3%)		
	Level 5	1831 (2.9%)	8 (1.3%)		
Emergency					
	Yes	57,729 (93.0%)	577 (95.2%)		0.043
	No	4345 (7.0%)	29 (4.8%)		
Intention					
	Nonintentional	57,108 (92.0%)	519 (85.6%)		NA*
	Self-harm/Suicide	1676 (2.7%)	63 (10.4%)		
	Assault	3228 (5.2%)	24 (4.0%)		
	Others	62 (0.1%)	0 (0.0%)		
Injury Mechanism					
	Traffic accident	17,567 (28.3%)	173 (28.5%)		NA*
	Falling	7201 (11.6%)	113 (18.6%)		
	Slip down	22,098 (35.6%)	154 (25.4%)		
	Collision	9994 (16.1%)	66 (10.9%)		
	Cut/Stab	4842 (7.8%)	99 (16.3%)		
	Machine	372 (0.6%)	1 (0.2%)		
Transport Interval	Mean ± SD	33.4 ± 17.0	35.7 ± 17.1	33.4 ± 17.0	0.001
Total GCS	Mean ± SD	14.6 ± 1.7	13.3 ± 3.3	14.5 ± 1.8	<0.001
ISS	Mean ± SD	9.2 ± 8.1	15.7 ± 12.5	9.4 ± 8.3	<0.001
SBP	Mean ± SD	140.0 ± 25.3	69.3 ± 23.7	139.4 ± 26.2	<0.001
DBP	Mean ± SD	81.1 ± 14.8	53.9 ± 14.9	80.8 ± 15.0	<0.001
MAP	Mean ± SD	100.7 ± 16.4	64.5 ± 16.5	100.4 ± 16.8	<0.001
PP	Mean ± SD	59.0 ± 20.1	31.6 ± 12.8	58.7 ± 20.3	<0.001
PR	Mean ± SD	85.2 ± 16.0	88.8 ± 23.9	85.2 ± 16.1	<0.001
RR	Mean ± SD	18.9 ± 2.0	19.6 ± 4.7	18.9 ± 2.1	0.001
BT	Mean ± SD	36.7 ± 0.5	36.4 ± 0.7	36.7 ± 0.5	<0.001
SpO_2	Mean ± SD	97.7 ± 2.2	96.8 ± 3.9	97.7 ± 2.2	<0.001
ROUTE					
	Direct	61,453 (99.1%)	600 (99.0%)		0.741
	Transfer	559 (0.9%)	6 (1.0%)		
	Outpatient referral	51 (0.0%)	0 (0.0%)		
	Others	11 (0.0%)	0 (0.0%)		
Outcome					
	Alive	62,032 (99.9%)	588 (97.0%)		<0.001
	Death	42 (0.1%)	18 (3.0%)		

*Transport Interval, time interval from scene to ED; GCS: Glasgow Coma Scale; ISS: Injury Severity Score; SBP: systolic blood pressure; DBP: Diastolic blood pressure; MAP: Mean arterial pressure; PP: Pulse pressure; PR: Pulse rate; RR: Respiratory rate; BT: Body temperature; SpO_2: oxygen saturation; ROUTE: Visit route; SD: Standard deviation; EMC: Emergency medical center; KTAS: Korean Triage and Acuity Scale. *p-value could not be calculated using chi-square approximation due to small expected counts; exact test was applied.*

TABLE 3. Demographic and general characteristics associated with pulse pressure.

Name	Description	PP ≥30 mmHg (N = 60,573)	PP <30 mmHg (N = 2107)	Total (N = 62,680)	*p*
Age (yr)	Mean ± SD	53.7 ± 22.9	46.9 ± 22.4	53.5 ± 22.9	<0.001
Sex					
	Female	26,046 (42.9%)	923 (43.4%)		0.508
	Male	34,527 (57.1%)	1184 (56.6%)		
Hospital Level					
	Regional EMC	18,535 (30.6%)	775 (36.8%)		<0.001
	Tertiary EMC	42,038 (69.4%)	1332 (63.2%)		
KTAS					
	Level 1	121 (0.2%)	27 (1.3%)		
	Level 2	2786 (4.6%)	293 (13.9%)		
	Level 3	19,929 (32.9%)	708 (33.6%)		NA*
	Level 4	35,980 (59.4%)	1009 (47.9%)		
	Level 5	1757 (2.9%)	70 (3.3%)		
Emergency					
	Yes	56,333 (93.0%)	2008 (95.3%)		<0.001
	No	4240 (7.0%)	99 (4.7%)		
Intention					
	Nonintentional	55,848 (92.2%)	1818 (86.3%)		
	Self-harm/Suicide	1575 (2.6%)	160 (7.6%)		NA*
	Assault	3089 (5.1%)	126 (6.0%)		
	Others	61 (0.1%)	2 (0.1%)		
Injury Mechanism					
	Traffic accident	17,142 (28.3%)	573 (27.2%)		
	Falling	7026 (11.6%)	299 (14.2%)		
	Slip down	21,685 (35.8%)	622 (29.5%)		<0.001
	Collision	9692 (16.0%)	320 (15.2%)		
	Cut/Stab	4664 (7.7%)	278 (13.2%)		
	Machine	363 (0.6%)	15 (0.7%)		
Transport Interval	Mean ± SD	33.3 ± 17.0	34.6 ± 17.6	33.4 ± 17.0	0.004
Total GCS	Mean ± SD	14.6 ± 1.7	13.9 ± 2.7	14.5 ± 1.8	<0.001
ISS	Mean ± SD	9.0 ± 7.8	14.8 ± 12.2	9.4 ± 8.3	<0.001
SBP	Mean ± SD	140.4 ± 25.7	109.0 ± 22.1	139.4 ± 26.2	<0.001
DBP	Mean ± SD	80.7 ± 14.7	85.7 ± 21.6	80.8 ± 15.0	<0.001
MAP	Mean ± SD	100.6 ± 16.5	93.6 ± 21.4	100.4 ± 16.8	<0.001
PP	Mean ± SD	59.9 ± 19.5	23.6 ± 4.8	58.7 ± 20.3	<0.001
PR	Mean ± SD	85.1 ± 15.9	89.4 ± 19.0	85.2 ± 16.1	<0.001
RR	Mean ± SD	18.9 ± 2.1	19.2 ± 2.6	18.9 ± 2.1	<0.001
BT	Mean ± SD	36.7 ± 0.5	36.6 ± 0.6	36.7 ± 0.5	<0.001
SpO_2	Mean ± SD	97.7 ± 2.1	97.4 ± 3.3	97.7 ± 2.2	0.003
ROUTE					
	Direct	60,025 (99.1%)	2092 (99.3%)		
	Transfer	545 (0.9%)	15 (0.7%)		0.742
	Outpatient referral	2 (0%)	0 (0%)		
	Others	1 (0%)	0 (0%)		
Outcome					
	Alive	60,528 (99.9%)	2092 (99.3%)		<0.001
	Death	45 (0.1%)	15 (0.7%)		

*Transport Interval, time interval from scene to ED; GCS: Glasgow Coma Scale; ISS: Injury Severity Score; SBP: systolic blood pressure; DBP: Diastolic blood pressure; MAP: Mean arterial pressure; PP: Pulse pressure; PR: Pulse rate; RR: Respiratory rate; BT: Body temperature; SpO_2: oxygen saturation; ROUTE: Visit route; SD: Standard deviation; EMC: Emergency medical center; KTAS: Korean Triage and Acuity Scale. *p-value could not be calculated using chi-square approximation due to small expected counts; exact test was applied.*

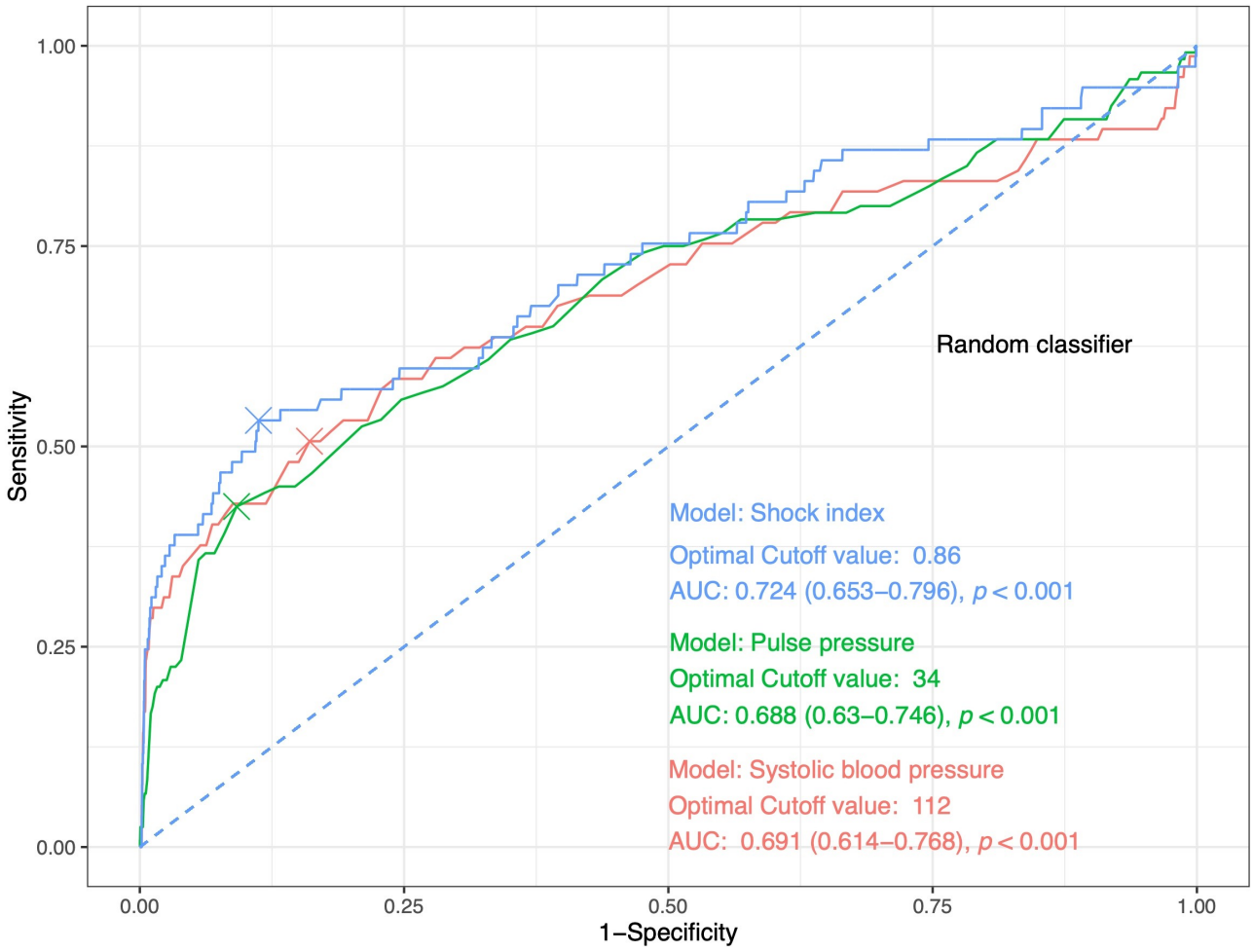

FIGURE 2. ROC curve analysis of SBP, PP and SI. Comparison among the three models revealed no significant differences under DeLong's test, even though each model individually demonstrates statistical significance. ROC: Receiver operating characteristic; SI: Shock index; PP: Pulse pressure; SBP: Systolic blood pressure; AUC: area under the curve. A diagonal dotted line presents the performance of a random classifier.

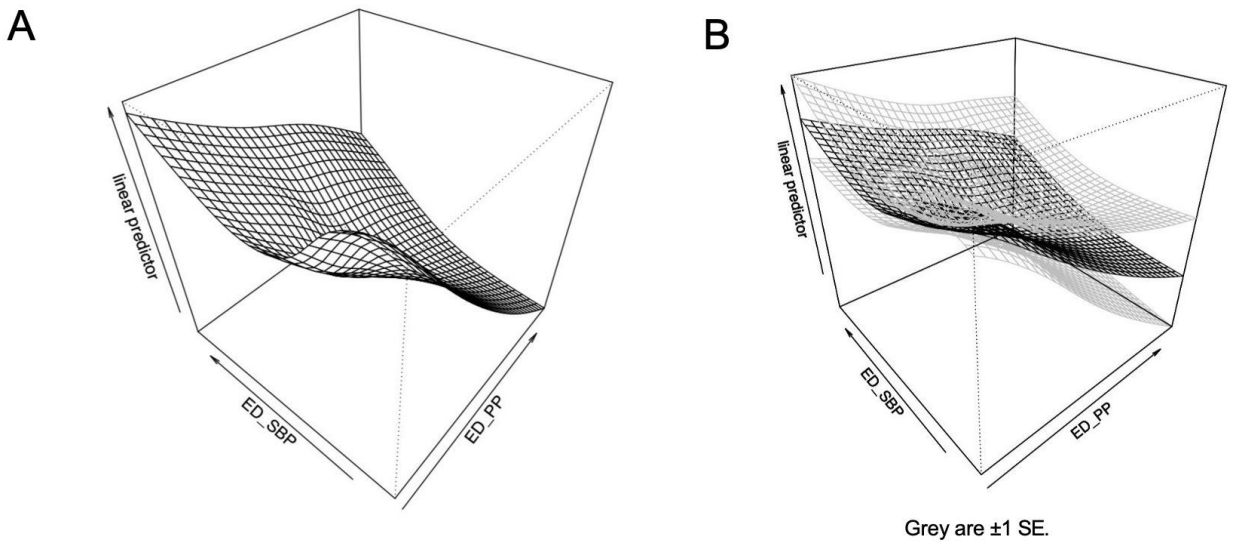

FIGURE 3. Interaction on mortality diagram of SBP and PP performed by GAM. (A) Mortality over SBP shows a bimodal pattern. Mortality over PP shows a decrescendo pattern. The interaction between extremes of SBP and low PP dramatizes mortality. (B) The figure on the right shows added confidence intervals with ±1 standard error (SE). ED_SBP: Systolic blood pressure measured at the emergency department; ED_PP: Pulse pressure measured at the emergency department; GAM: Generalized additive model.

4. Discussion

Although all patients experiencing shock require rapid intervention, traumatic injuries tend to worsen rapidly. Studies have indicated that a significant proportion of deaths resulting from trauma with shock occur within the first 24 hours owing to hypovolemic shock [2, 3]. In cases of major trauma, the majority of fatalities occur within the initial hours post-injury, with hemorrhage responsible for 30%–40% of these deaths [4]. Early resuscitation and transfusion are vital in preventing mortality; however, hypotension is often not identified until the patient reaches a class III shock status, characterized by blood loss exceeding 30% [5, 6].

Current methods for predicting mortality in trauma vary widely, as no single hemodynamic index has been definitively identified as superior. Although SBP is generally considered a reliable indicator of cardiac performance, its correlation with cardiac output may be unreliable in conditions such as cardiogenic shock [7]. DBP, which reflects vascular tone, can provide additional insights into clinical outcomes. For instance, high DBP in pediatric patients with refractory septic shock has been associated with a better prognosis, potentially because it indicates a cardiogenic origin [8]. Similarly, a DBP >70 mmHg measured after resuscitation has been shown to be an independent predictor of survival [9]. However, DBP does not always correlate with overall diastolic perfusion pressure owing to variations in systemic vascular resistance and arteriolar critical closing pressure.

PP and SI further illustrate the challenges of hemodynamic assessment. PP, indicative of regional blood flow and arterial stiffness, is variably associated with mortality, with a narrow PP and high DBP often serving as early markers of blood loss and decreased venous capacitance [10]. In addition, while high PP values in the first 24 hours after extracorporeal cardiopulmonary resuscitation have been reported as independent predictors of survival [11], PP >48 mmHg in septic shock populations has been independently associated with 28-day mortality [12]. Moreover, a J-shaped relationship between PP and all-cause mortality was observed in patients with ischemic heart failure, with statistical significance reached only when SBP exceeded 110 mmHg [13]. Similarly, both a narrow PP and elevated SI have been linked to increased mortality in trauma patients requiring massive transfusion [14], and a novel PP/Heart rate ratio has demonstrated moderate predictive ability for transfusion needs [15]. Despite these findings, neither mean arterial pressure (MAP) nor PP fully accounts for age-related changes in blood pressure [16].

Although each of these hemodynamic variables shows promise for predicting mortality, their associations vary significantly with the underlying pathology. Understanding the complex interactions among these indices may provide a more robust framework for mortality prediction than relying on any single parameter alone. Our findings emphasize the importance of examining these interactions to capture the nuances of the shock state. By visualizing the interconnected nature of these variables, we gain insights that could lead to the development of a more accurate and comprehensive risk stratification model. Future research should integrate these interactions into predictive models to facilitate prompt recognition of severely ill patients and guide timely, effective interventions [17–19].

In Korea, where this study was based, the KTAS level and emergency status are determined at the triage level upon hospital arrival. In contrast, the selection of the transport hospital and transportation time are decided during the pre-hospital phase, led by the EMS. The KTAS scale begins by evaluating life-threatening conditions. Then, it assesses the patient's main complaint while considering additional factors such as vital signs, consciousness level, pain severity, mechanism of injury, and blood sugar levels. The assigned levels are resuscitative, urgent, emergent, semi-emergency and non-emergent from Level 1 to Level 5 [20]. According to this study, patients who ultimately died were classified under emergency cases with low KTAS levels, indicating that the triage evaluation was, to some extent, appropriate. However, it was found that not only the transportation time was longer, but a higher proportion were transferred to regional hospitals rather than tertiary centers in the deceased group, suggesting that the pre-hospital evaluation of the transport phase was not appropriate. We believe that clarification of the relationship between hemodynamic indices and mortality would significantly enhance the accuracy of severity evaluation and hospital selection in the pre-hospital phase, as assessments are currently inadequate.

In contrast to previous investigations that focused on the predictive value of individual hemodynamic indices, our study reveals that relying on isolated parameters may be insufficient for accurate mortality prediction in trauma patients. While conventional ROC analysis showed that SBP, PP and SI each had moderate predictive value, no significant differences were observed when these indices were considered separately. Notably, our results demonstrated a significant correlation between SBP and SI, which led us to explore the interaction between SBP and PP using a GAM. This analysis uncovered a novel, nonlinear and bimodal relationship between SBP and mortality—particularly highlighting that low PP markedly amplifies mortality risk at both extremes of SBP. These findings suggest that an integrated approach combining SBP and PP provides a more refined understanding of hemodynamic alterations in trauma patients, thereby enhancing early risk stratification and informing more targeted clinical interventions.

This study has several limitations. First, it is a retrospective analysis based on a pre-existing database, which did not include detailed information regarding interventions or first-aid measures that could have influenced mortality outcomes. Additionally, specific mechanisms of trauma, such as penetrating, blunt or head injuries, which may have differential impacts on patient outcomes, were not considered. The analysis also did not account for the effects of comorbidities or pre-existing health conditions. Second, the scope of this study was restricted to traumatic shock. Additional research is needed to explore the applicability of these findings to other types of shock, including septic and cardiogenic shock. Since the data were exclusively derived from Seoul, Korea, further research is required to determine whether these results are generalizable to different populations and regions. Lastly, while the study emphasizes the importance of promptly recognizing shock, future investigations should evaluate whether the insights gained

from these hemodynamic indices can inform the development of optimal resuscitation targets in broader clinical contexts.

5. Conclusions

The interaction effect of PP and SBP on mortality was confirmed using GAM. This consideration is crucial for optimizing patient care and ensuring effective management of emergency trauma situations. This finding would not only assist triage evaluation, but also significantly enhance prehospital evaluation at the transportation level.

AVAILABILITY OF DATA AND MATERIALS

The data that support the findings of this study are available from the Seoul Golden Time Board, but restrictions apply to the availability of these data, which were used under license for the current study and are not publicly available. However, the data are available from the authors upon reasonable request and with the permission of the Seoul Golden Time Board.

AUTHOR CONTRIBUTIONS

KL and YS—drafted the work and were major contributors to the manuscript. YC and GC—collected the data from the Seoul Golden Time Registry. YS and TP—analyzed and interpreted the data regarding hemodynamic indices and mortality in patients with trauma. All authors contributed equally to all the other sections. All the authors have read and approved the final version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study utilized data from the Seoul Golden Time Registry, a registry designed for quality control and enhancement of the emergency medical system in Seoul, South Korea. The registry collects and analyzes data to improve patient outcomes in emergency care. Given the nature of the study, a waiver for obtaining participants' informed consent was granted by the Institutional Review Board of Kangdong Sacred Heart Hospital (IRB No. KANGDONG 2024-09-002).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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